An automated approach to magnetic divertor configuration design

M. Blommaert[1], W. Dekeyser[2], M. Baelmans[2], N. Gauger[3], D.Reiter[1]

1 Institute of Energy and Climate Research, Plasma Physics (IEK-4), FZ Jülich GmbH, EURATOM Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany
2 Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300A, 3001 Leuven, Belgium
3 Department of Mathematics and Center for Computational Engineering Science, RWTH Aachen University, Schinkelstr. 2, D-52062 Aachen, Germany

JÜLICH FORSCHUNGSZENTRUM

The first fusion reactor ITER is currently under construction in Cadarache, France and fusion power plant conceptual design activities are intensified in Europe, US and Asia. Within this context the transition from advancements in more fundamental plasma physics research towards (computational) engineering and design is regarded as urgent in all ITER partner states. One important component that needs special attention is the so called "divertor". It is designed to modify the magnetic field configuration such that strong plasma flows develop towards particular high heat flux wall components of the reactor vessel. Even on the most powerful supercomputers available today, divertor design is extremely CPU demanding, not least due to the large number of design variables and the hybrid micro-macro character of the flows. Therefore, automated design methods based on optimization can greatly assist current reactor design studies. An approach is developed to optimize the magnetic field configuration, using a somewhat reduced model for the plasma edge. The design objective is to spread the target heat load as much as possible, while maintaining the full helium ash removal capabilities of the pumping system.

Optimization problem

$$\min_{\phi\in\Phi_{ad},q_1,q_2} I(\phi,q_1,q_2)$$
$$\text{s.t.}\quad c_1(\phi,q_1)=0,\quad c_2(q_1,q_2)=0,\quad h(\phi,q_1)\geq 0,$$

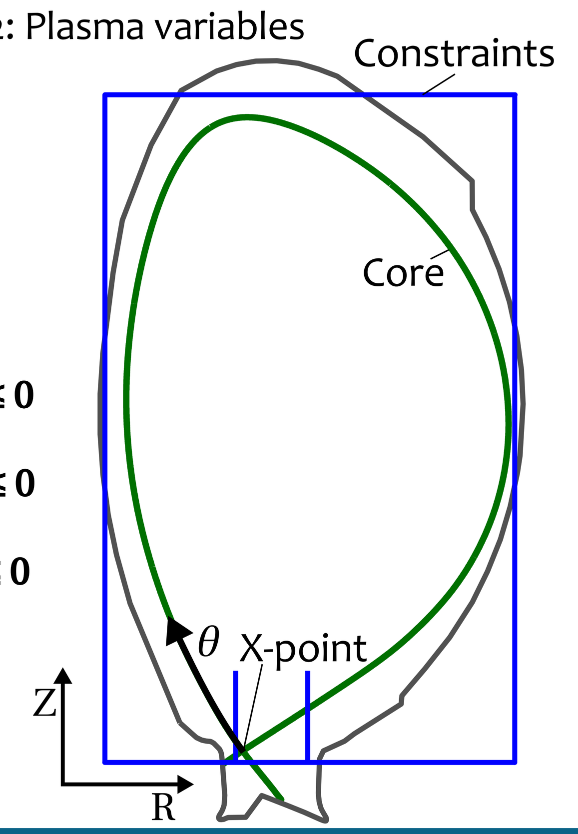
ϕ: Control currents
c1: Magnetic field model
c2: Plasma model
h: Nonlinear stability constraints
q1: Magnetic field variables
q2: Plasma variables

Or in reduced form:

$$\min_{\phi\in\Phi_{ad}} \hat{I}(\phi)\quad \text{s.t.}\quad \hat{h}(\phi)\geq 0,$$

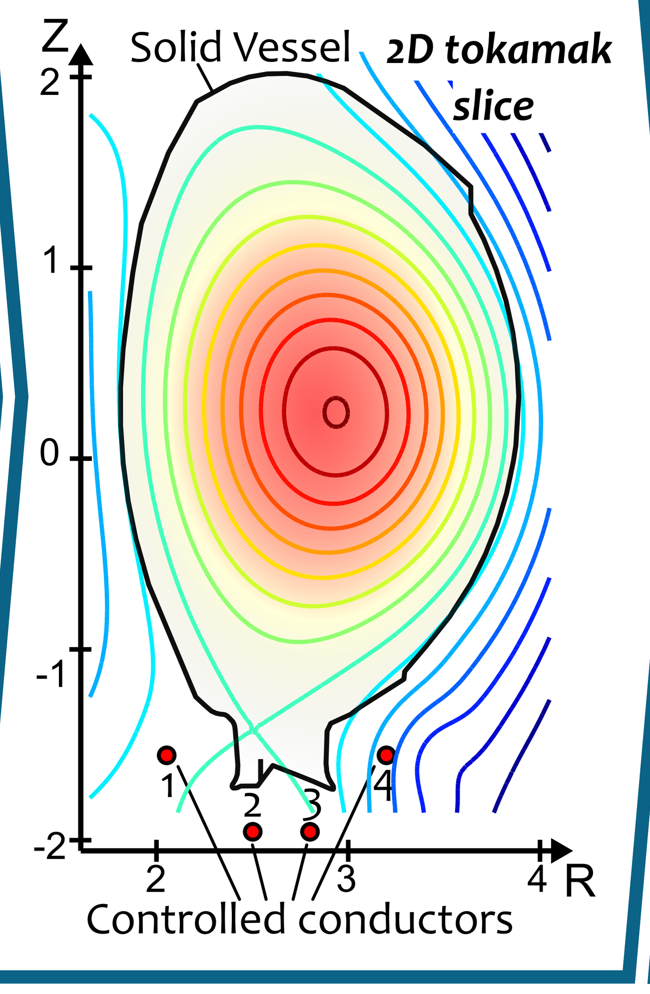
With following **constraints** on core shape

$$h(1)=\max_{\theta\in\theta_{core}}(R_{core}(\theta))-R_{max}\leq 0$$
$$h(2)=\max_{\theta\in\theta_{core}}(Z_{core}(\theta))-Z_{max}\leq 0$$
$$h(3)=R_{min}-\min_{\theta\in\theta_{core}}(R_{core}(\theta))\leq 0$$
$$h(4)=Z_{min,x}-Z_x\leq 0$$
$$h(5)=R_{min,x}-R_x\leq 0$$
$$h(6)=R_x-R_{max,x}\leq 0$$



Set-up

Control currents through **shaping conductors**



Magnetic field computation

Use perturbation approach to avoid full MHD calculations

- Starting from

$$\Delta^*\Psi_0+\Delta^*\delta\Psi=-\mu_0 R(J_{\phi,0}+\delta J_{\phi,int}+\delta J_{\phi,ext})$$

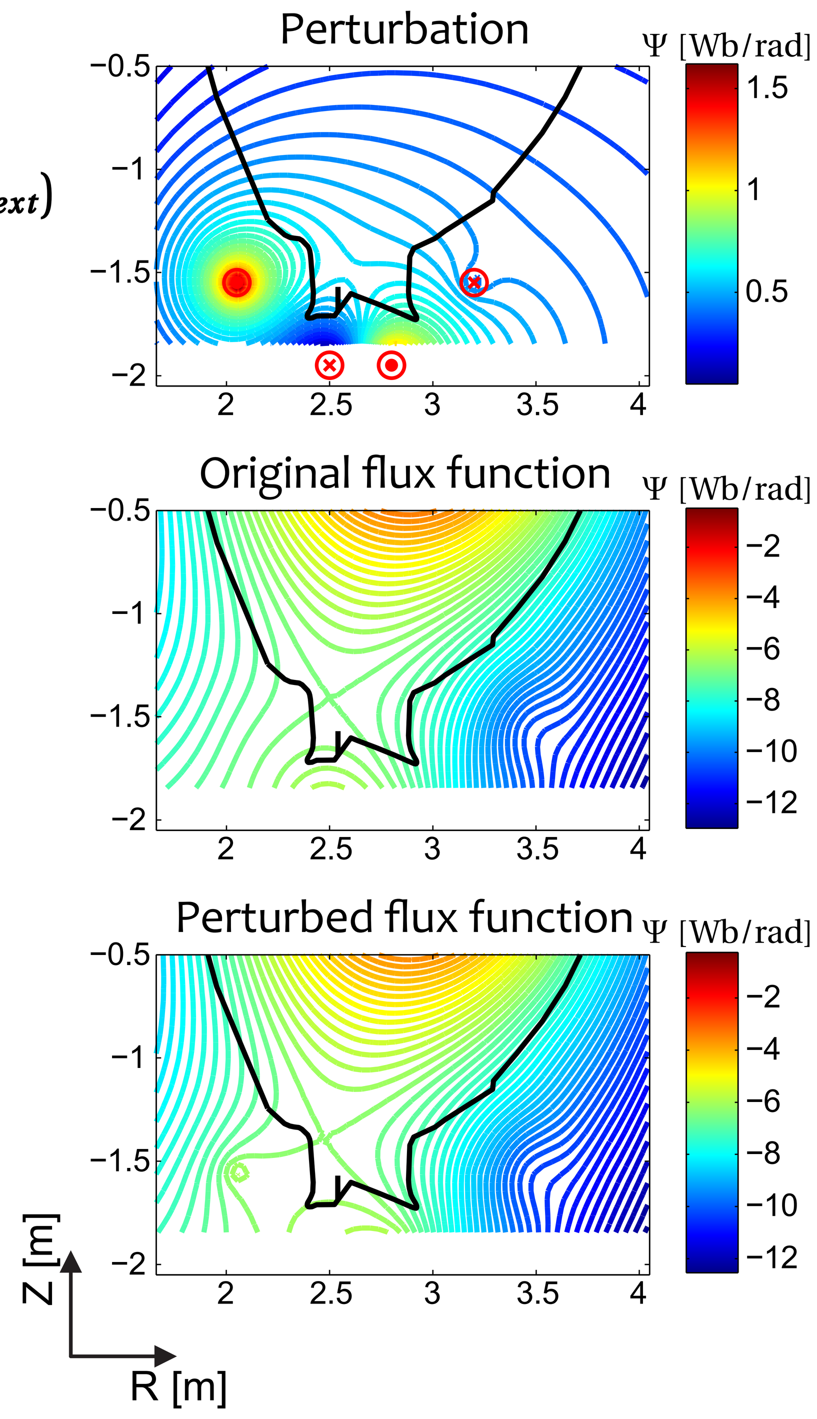
Original — Perturbation

- Calculate effect of additional conductors in vacuum

$$\Delta^*\delta\Psi=-\mu_0 R\left(\underbrace{\delta J_{\phi,int}}_{\approx 0}+\delta J_{\phi,ext}\right)$$

- **Add** perturbation flux function to reference

$$\Psi=\Psi_0+\delta\Psi$$



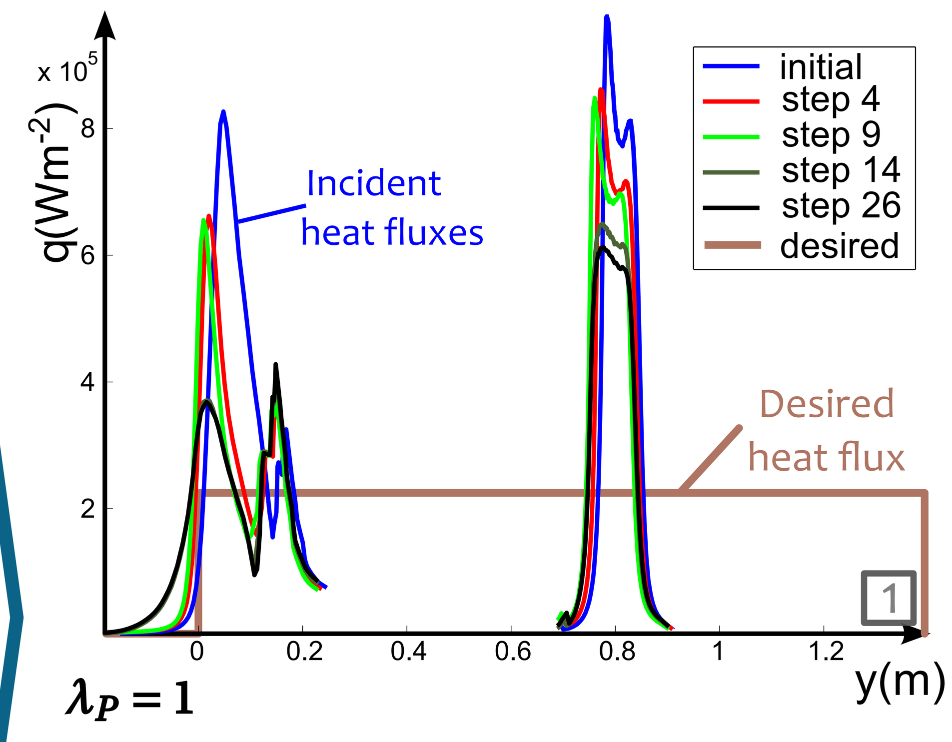
Next iteration

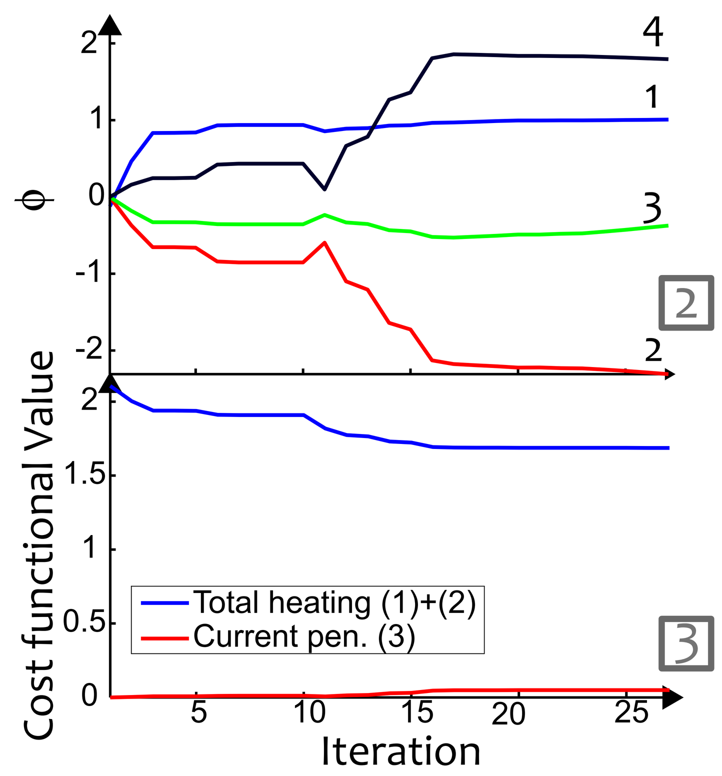
Optimization

Solution through:

- **SQP** Optimization
- **FD** gradient computation
- **Bracketing** line search with Wolfe conditions
- **Gradient projection** optimization subproblem

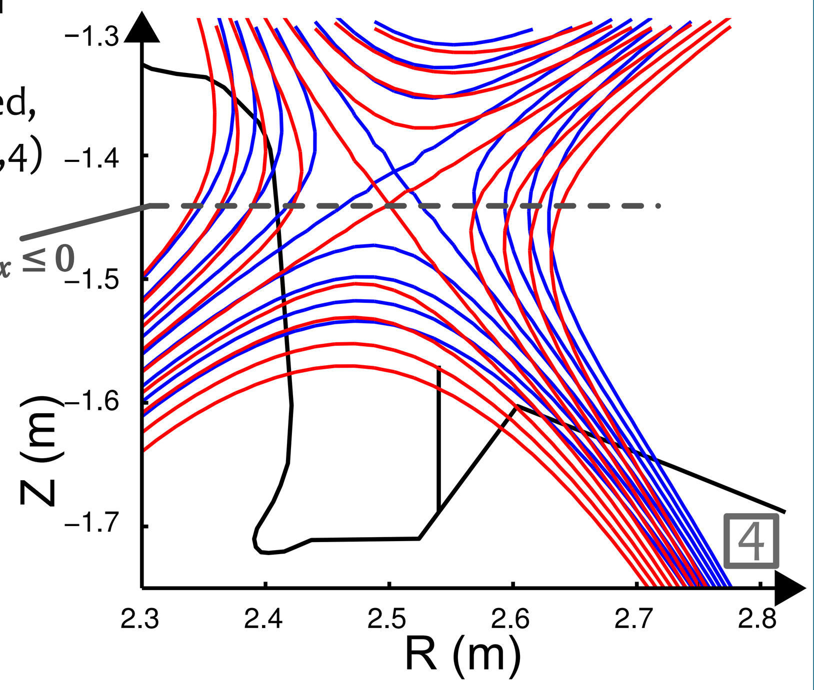
Results

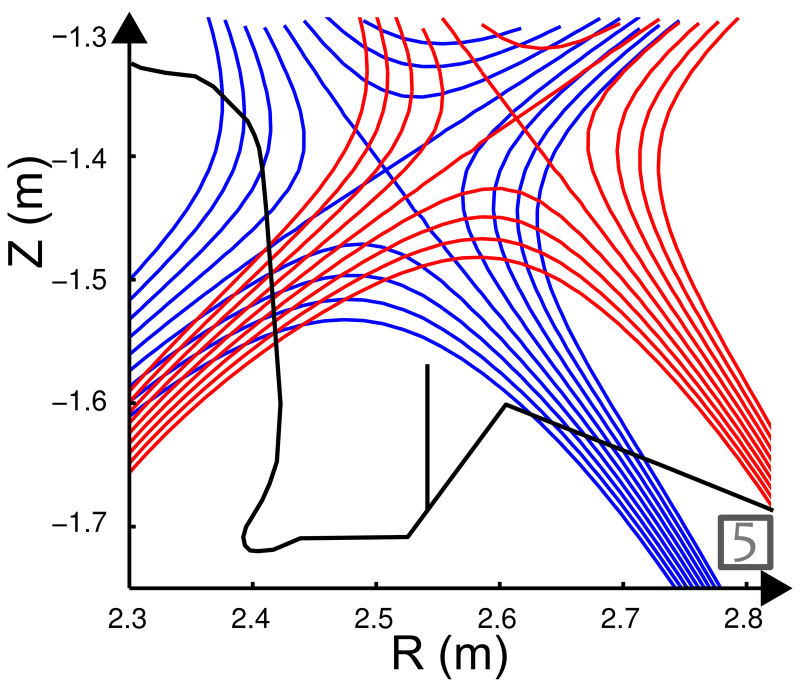




$\lambda_P=1$

- Heat peaks are lowered (fig 1) during optimization to lower cost functional value (fig 3)
- Current couples with opposing currents are formed, widening the flux tubes towards target area (fig 2,4)
- The optimum is found to be at the boundary of the h(4) constraint (fig 4) $h(4)=Z_{min,x}-Z_x\leq 0$

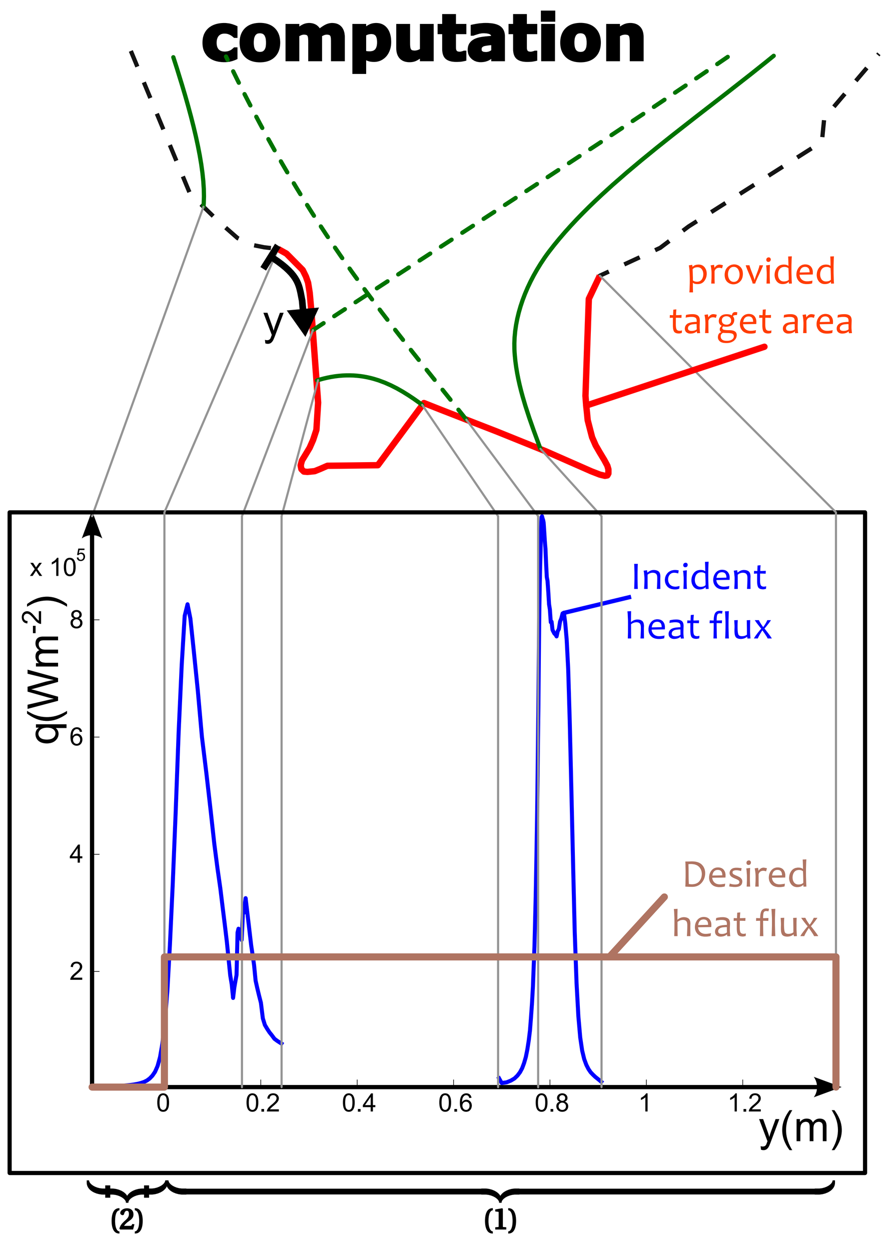




$\lambda_P=10$

- The optimization pushes the separatrix towards the center of the target area to avoid high penalty (fig 5)
- This increases the heat peaks at the target but reduces the parallel heat flux outside the target area to zero.
- No active constraints, current penalty limits field shifting

Cost functional computation

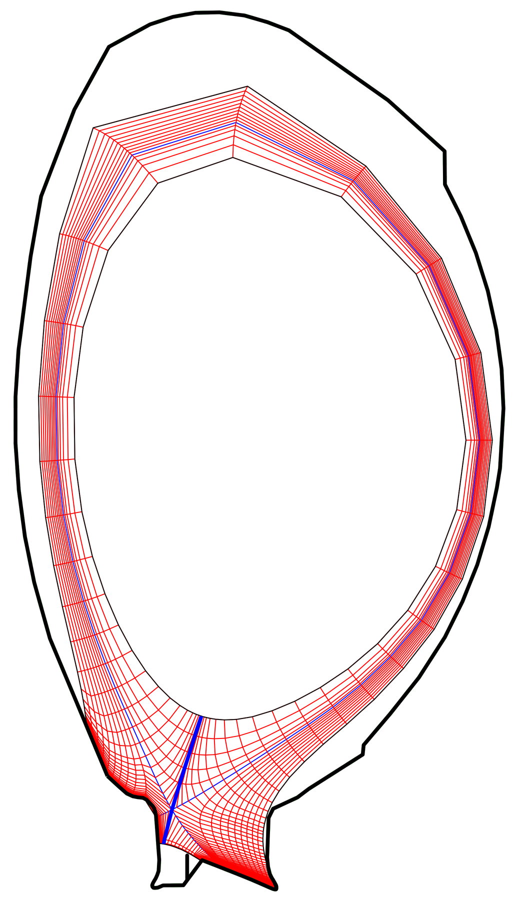


$$I(q,\phi)=\frac{1}{2}\lambda_Q\left(\underbrace{\int_{\Gamma_t}[Q_\perp-Q_{d,t}]^2\,d\sigma}_{(1)}+\underbrace{\int_{\Gamma_P}[\lambda_P(Q_\perp-Q_{d,p})]^2\,d\sigma}_{(2)}\right)+\underbrace{\frac{1}{2}\lambda_\phi\sum_i\phi_i^2}_{(3)}$$

(1) Maximal target heat load spreading
(2) Wall heating penalty
(3) Current penalty, regularization term

Grid generation

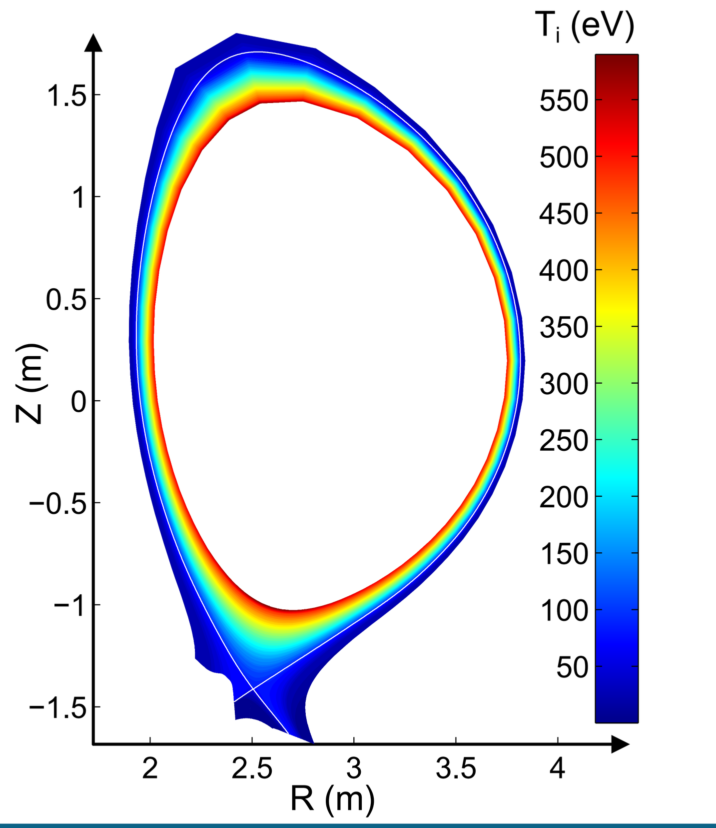
Strong **anisotropic transport** in physics
→ Create **grid aligned** with magnetic field



Plasma flow simulation

Solve **plasma edge** conservation equations

- **Ion continuity** equation
- Ion **parallel momentum** equation
- Internal **energy** equation
  - Sum of ion, electron and neutral internal energy equations
  - $T=T_i=T_e=T_n$
- **Neutral continuity** equation
  - Pressure diffusion equation
- State variables: n_i, n_n, $u_{//}$, T



Conclusions

- Optimization framework with FD gradient calculation **succesfully adjusts the magnetic field design to reduce the heat peak** at the target area
- When increasing the relative importance of the **heat flux outside the target area**, the **optimization avoids using all non-target material** as desired
- **Plasma edge simulation are computationally extremely expensive**, even for this reduced model and limited set of control variables

Future work

- Use **adjoint gradient calculation** to allow for **more control variables** and **reduce computational costs**
- **Extend magnetic model** to allow larger changes to the magnetic configuration
- Incorporate more MHD-stability criteria, to **account for unstable configurations** in the optimization results